Investigation of Pencil and Bifurcated Beam Fed Cylindrical Dielectric Lens Antenna for 5G Mobile Base Stations

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***Abstract*—This research investigates the cylindrical dielectric lens antenna to be replaced with present linear arrays in order to reduce number of the feed elements and ease the fabrication process. Ray tracing method is employed by MATLAB program to investigate and design the lenses. Various beam radiations are adequately investigated in order to obtain the desired radome structure. Dielectric lenses usually have a convex shape, which offers high thickness geometry. To overcome this drawback, first a pencil beam radiation was studied. This structure possesses a high loss due to a significant increase in the refractive index. In the next step bifurcated beam was investigated and a concave shaped lens was obtained. As a result, the lens was remarkably decreased in its thickness and size to be replaced with the radome structure.**

***Index Terms*—5G Technology; Dielectric Lens Antenna (DLA); Mobile Base Station; Antenna Radome; Slow-Wave Lens.**

I. Introduction

To meet the low sidelobe requirement of the base station antenna, linear arrays has been widely employed in which the radiating elements usually have similar structure. For low sidelob radiation pattern synthesis, all array elements are excited in different amplitude and phase. This needs complicated feeding circuit composed of power dividers and phase shifters. Therefore, this feeding circuit is suffered from a feeding loss and limit the wide frequency band usage. For 5G application, higher frequency usage and multi frequency operations are required. The present approach of linear arrays should be reconsidered. Introduction of a lens antenna shown in Figure 1 is a promising candidate to overcome these challenges. Features of this antenna are to reduce the amount of the feed radiators to only one element and radiation pattern synthesis by dielectric lens shaping.

In recent years, lens antennas have obtained great attention of the researchers in wireless communications due to providing a stable beam profile and high directivity in wide beam scanning range. Regarding to the phase velocity in the lens medium, there are two types of dielectric lens antennas (DLAs) and metal-plate lens antennas [1] in which the electrical path length is increased and decreased, respectively. To obtain a practical solution, the focus of this paper is on the natural dielectric lens antennas.

There are various types of the lens reported to cover a wide beam range. A Luneburg DLA is proposed in [2] for beam scanning applications. In this type of the lens, the refractive index is varied along the radius, offering a complicated structure.

Integrated DLAs fed by focal arrays were investigated in [3, 4]. In these designs, which are radially symmetrical, the Abbe's Sine condition is applied in order to avoid the off-axis spherical and comatic abbreviations. The antennas exhibit wide angle beam scanning on scanning planes, however the performances are decreased on transverse planes.

On the other hand, there are some reports using metal-plate lens antennas for wide range beam scanning [5, 6]. The exhibited beam angles for these designs are limited to specific ranges due to the nature of their structures.

In [7] a cylindrical Negative Refractive Index (NRI) lens is proposed for mobile base stations. In this design the antenna radome is replaced with the lens to achieve low side-lobe radiation. It was shown that by using the metamaterial, the overall size of the antenna can be miniaturized owing to shortening the focal length.

In this paper the cylindrical dielectric lens radome fed by pencil beam and bifurcated beam radiations is investigated to be replaced with array configurations in mobile base stations, with the aim to reduce the radiation elements and ease the fabrication process. The antenna configuration is designed using the Ray-tracing method in MATLAB software.

II. Design Concept

The concept of applying cylindrical lens antenna for mobile base stations was proposed in [7] using NRI material which forms a concave shaped lens in order to reduce the size of the antenna. This paper intended to investigate the possibilities of replacing array configuration by DLA. The structure of the proposed cylindrical lens radome is shown in Figure 1. By employing the positive refractive index material, a convex shape geometry with comparably larger structure is expected. To overcome this drawback the parameters of the lens are investigated to obtain a semi-convex shape design.

III. Ray-tracing Method

The design parameters of the proposed dielectric lens are illustrated in Figure 2. In order to trace the inner contour, polar coordinates and the outer contour, rectangular coordinates are applied. The following three simultaneous differential equations have been numerically solved using MATLAB code to generate the lens contour shapes.

The first condition to be met is the slope of the inner contour based on the Snell's law, as follows:

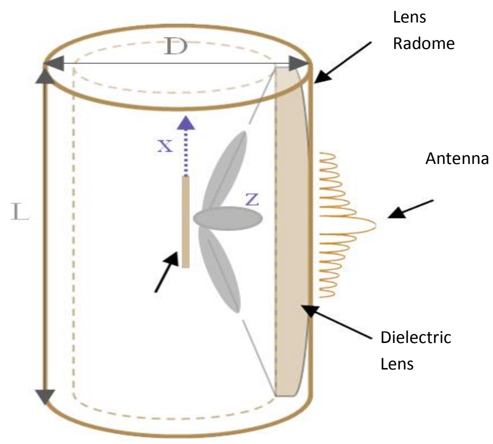

Figure 1: Cylindrical dielectric lens radome

$$\frac{dr}{d\theta} = \frac{nr\,[\![\sin(\theta-\theta]\!]')}{n\cos(\theta-\theta')-1} \tag{1}$$

Where n is the lens refractive index, or is the path length of the incident ray of the inner contour, θ is the incident angle of the wave on inner contour and θ' is the angle of the refraction of the wave inside the lens medium. With similar concept the slope of the lens at the outer contour is obtained as follows:

$$\frac{dz}{d\theta} = \frac{n\sin(\theta')}{1-n\cos(\theta')}\,\frac{dx}{d\theta} \tag{2}$$

In order to obtain the lens contour shape based on the desired aperture illumination, it is needed to define another equation. The relation between the feed radiation pattern, indicated by $E_p^2(\theta)$, and the aperture distribution, indicated by $E_d^2(\theta)$, is given by:

$$\frac{dx}{d\theta} = \frac{E_p^2(\theta)sin\theta}{\int_0^{\theta_m} E_p^2(\theta)sin\theta d\theta}\,\frac{\int_0^{x_m} E_d^2(x)xdx}{E_d^2(x)x} \tag{3}$$

For a base station radome with axi-symmetrical structure around the x axis, the above equation is simplified as follows:

$$\frac{dx}{d\theta} = \frac{E_p^2(\theta)}{\int_0^{\theta_m} E_p^2(\theta)d\theta}\,\frac{\int_0^{x_m} E_d^2(x)dx}{E_d^2(x)} \tag{4}$$

The proposed antenna is designed to be fed by an ideal cosine radiation located at the origin of the lens, which is defined by (4). Here, m expresses the sharpness of the beam. At $\theta_s = 0°$ the main beam is aligned with the z-axis, which produces a pencil beam pattern. When $\theta_s = 60°$, a bifurcated beam is produced. This concept is shown in Figure 3.

$$E_p^2(\theta) = \cos^{m}(\theta-\theta_s) \tag{5}$$

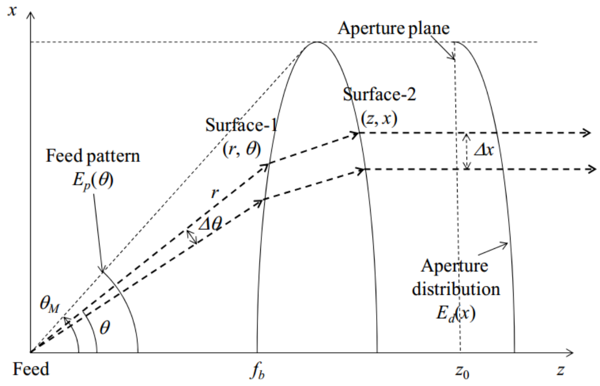

Figure 2: The geometry of the dielectric lens design formulated in polar (inner contour) and rectangular (outer contour) coordinates

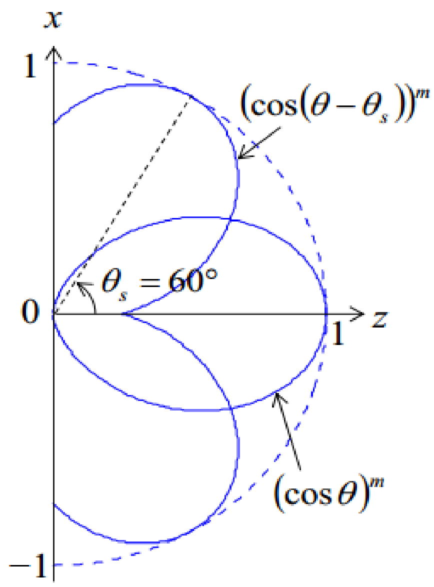

Figure 3: Rough sketch of feed point radiation pattern

The pattern of ideal cosine is applied in Equation (3) to attain the aperture distribution of the lens antenna which is defined by:

$$E_d^2(\theta) = \left(1-\left(1-\frac{1}{C}\right)\left(\frac{x}{x_m}\right)^2\right) \tag{6}$$

where, C is the edge level of the aperture distribution and x_m is the maximum radius of the outer surface. The radiation intensity decreases to a value of $1/C$ at the edge level of the lens as shown in Figure 4.

IV. Lens Shaping Design

Figure 5 illustrates a conventional dielectric lens structure. As it is shown, a dielectric lens, typically possess relatively high value of diameter and thickness which is not suitable to be replaced with a radome in mobile base stations.

In Ray Tracing method, the main parameters affecting the lens design are illustrated in Table 1. The refractive index as the main attribute of the chosen material indicates the ray refractions on the surfaces and the speed of the radiated wave inside the lens medium. The maximum angle from the radiating element to the lens edge is shown by θ_m.

Adequately adjusting this value is needed, since any excess of the feed radiation from this value cause the ray spill over. Normal vector angle to the horizontal axis which is defined by θ_0 is given based on the tracing the ray at the edge of the lens. The sharpness of the ideal radiation pattern, *m* and the edge level of the aperture distribution, *C* as important factors to obtain desired illumination characteristics are explicitly discussed in the next section.

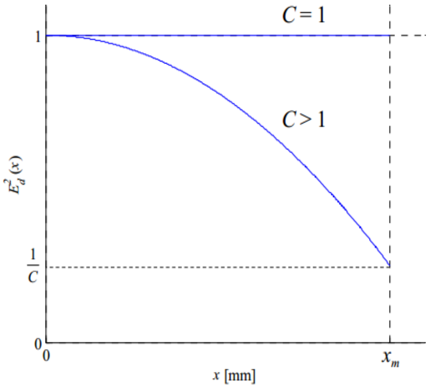

Figure 4: Rough sketch of the aperture distribution

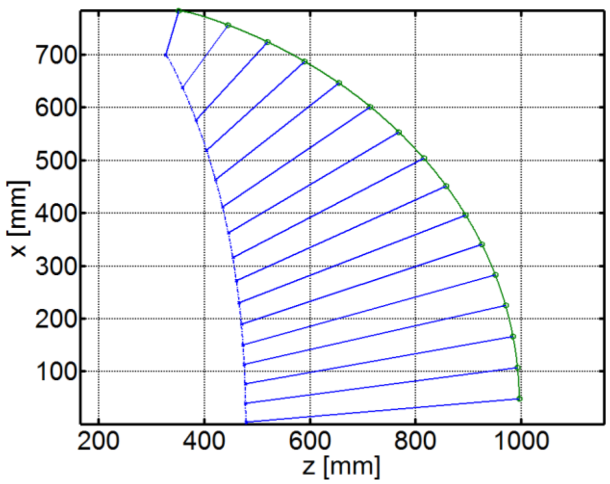

Figure 5: Conventional structure of a cylindrical DLA

Table 1
Design Parameters

Para.	Definition
n	Refractive index
θ_m	Maximum angle from the feed point to the lens edge
θ_0	At the lens edge, Normal vector angle to the horizontal axis
m	Beam sharpness of the feed pattern
C	Edge level of the aperture distribution

A. *Comparison Between E_d^2 And E_p^2*

In order to obtain a desired value of m, which represents a feed radiation and C, which defines an aperture distribution, a comparison between the respective patterns is performed. In this paper, the lens diameter is considered 350mm. In most of the cases, the value of Xm, is in the range of the lens diameter, specifically when the lens shape is straight and the lens edge is not dramatically tilted, which is our desired configuration. Therefore, to compare the patterns, we may initially consider Xm equal to 350mm. Figure 7 compares different aperture distributions of C=2, C=4 and C=8, with respect to the feed radiation patterns of m=2, m=4 and m=8. It is seen by decreasing the value of m from 8 to 2 and increasing the value of C from 2 to 4, a very good match is obtained between the patterns (Figure 6(a) and 6(b)). At C = 8 the aperture distribution bends at the edges of the lens, decreasing the matching condition (Figure 6(c)). As a result, feed radiation of m = 2 and aperture distribution of C = 4 are suitable candidates to be chosen as initial design specifications.

B. *Pencil Beam Design*

The radome size designed for the base stations should be small in size, in order to ensure the physical stability. To achieve this, the radome diameter based on the different values of the main parameters indicated in Table I, was investigated. In Figure 7, the matched values of *m* = 2 and *C* = 4 were applied to obtain the results with respect to to the different values of *n* = 2, 3.6, 10 and θ_m = 40º, 50º, 60º. It is seen that by increasing θ_m, from 40º to 60º, the radome diameter could be reduced, significantly. At θ_m = 40º it exceeds 500 mm while at the maximum angle of θ_m = 60º, the diameter has been remarkably decreased to below 310 mm for all values of *n*. At *n* = 10 a very thin and straight design is achieved. The relatively high value of *n* = 10 could be obtained using high permittivity materials such as homologous series of Strontium Titanate [8] which shows good performances at microwave and terahertz bands.

It was expected to see a big difference in lens structures with different refractive indexes of n = 2 and n = 10. However, owing to the good configuration of the parameters, the material effect has been decreased to a minimum.

C. *Bifurcated Beam Design*

In this section, the possibilities of the radome structures based on the bifurcated beam feeding are investigated. It is understood that at the radiation angle of θ_s= 60º, the diameter could be remarkably decreased in size. Figure 8 indicates the design results regarding to the different values of n = 2, 3.6 and 10 with respect to the θ_m variations. It is seen, that by increasing θ_m, the radome diameter could be mitigated, significantly from over than 250 mm at θ_m=65º down to lower than 170 mm for all configurations. Notice that, the high value of n = 10 and θ_m=85º, make it difficult to obtain a desired structure for the last configuration. In comparison with pencil beam radiation, which presented more smooth.

V. CONCLUSION

In this paper, the possibilities of replacing array configuration with a cylindrical lens radome for 5G mobile base stations were investigated using the Ray Tracing method. The initial design of a conventional cylindrical lens, possesses a structure with a considerably large diameter. In order to decrease the diameter of the radome, first pencil beam radiation was investigated. The length of the lens radome considered 700 mm. By adequately configuring the design parameters, it was shown that can achieve a smooth structure with a diameter below the half of the lens length (310 mm). Moreover, it was seen by employing bifurcated beam feeding and increasing the value of maximum angle from the feed point to the lens edge, it is possible to propose a lens radome with a decreased diameter by a very low value of half of the pencil beam design (less than 150 mm here).

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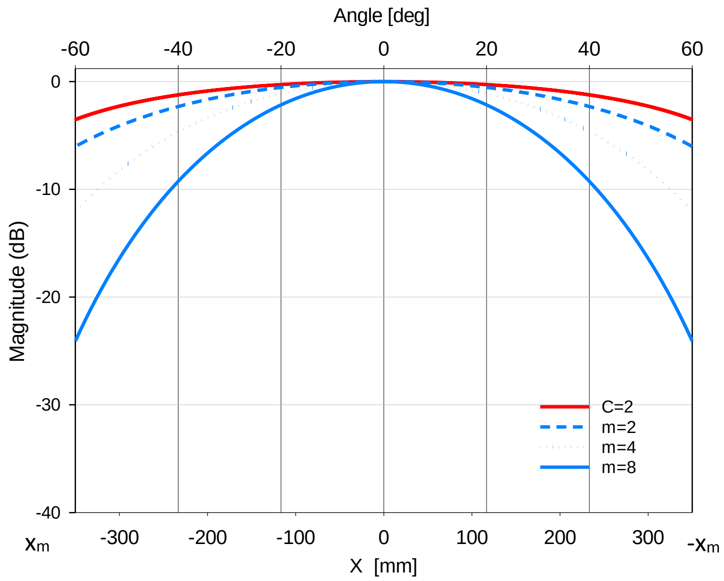
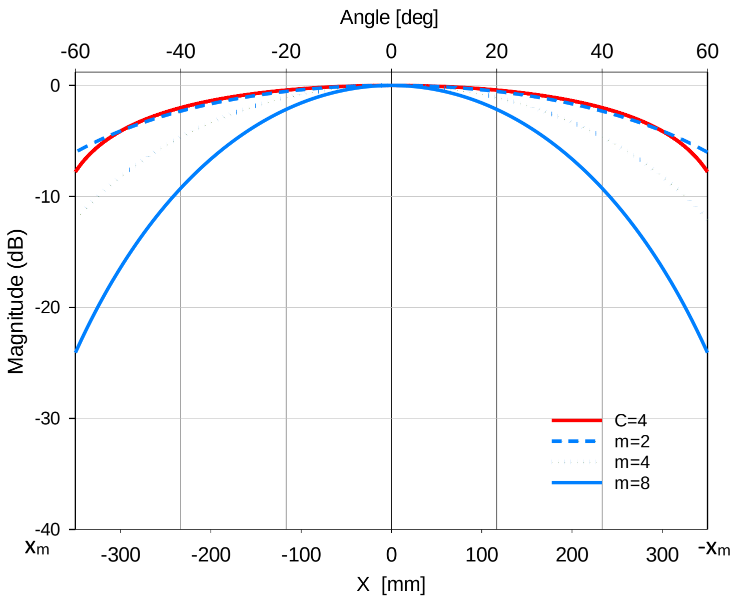


(a)



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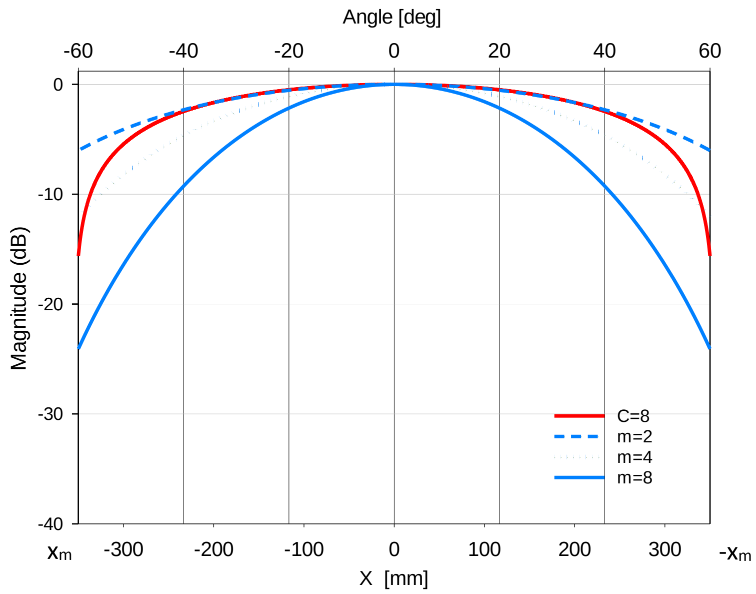

(c)

Figure 6: Comparison between $\boldsymbol{E}_d^2$ and $\boldsymbol{E}_p^2$ with respect to the different values of m at (a) C=2 (b) C=4 (c) C=8

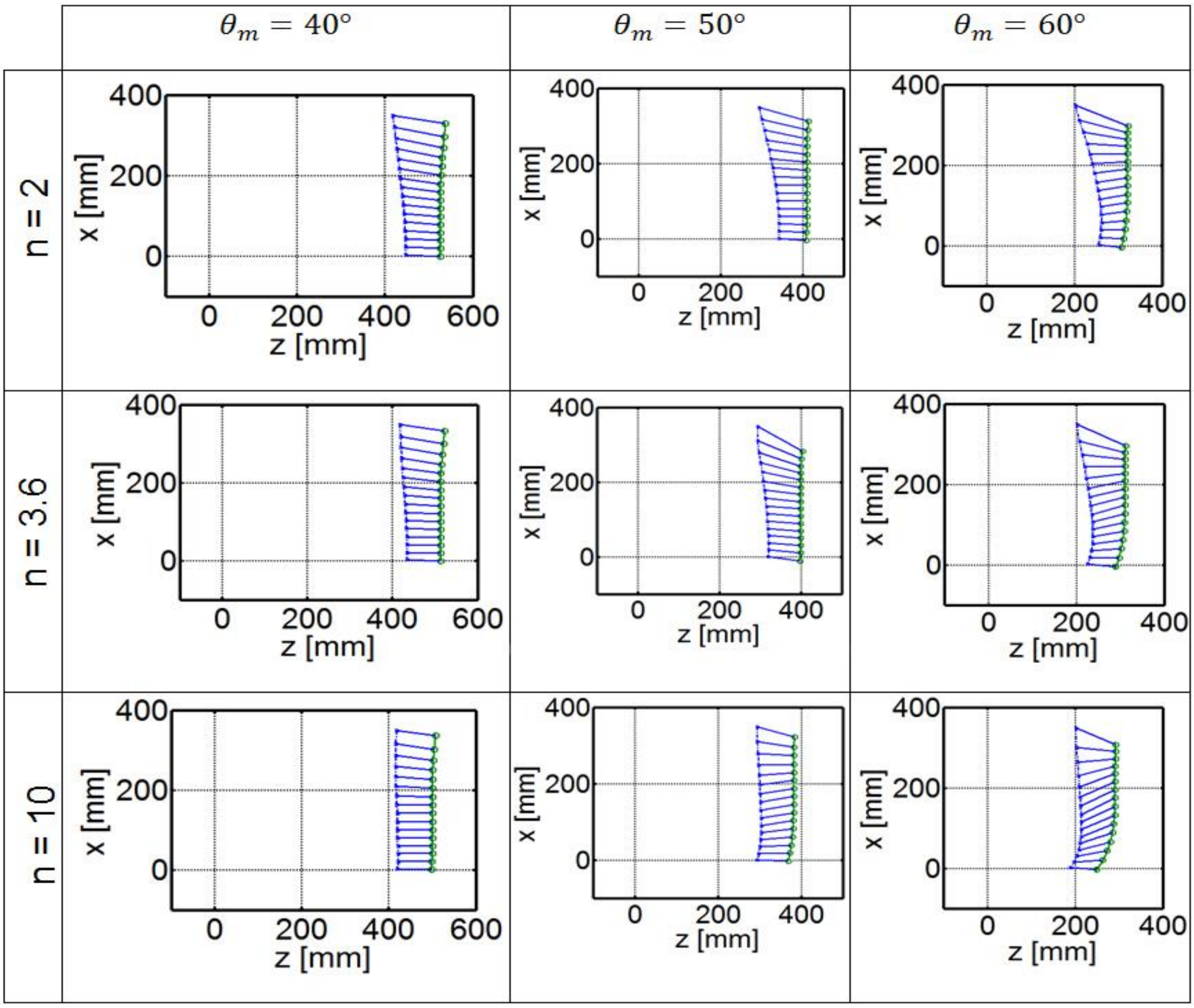

Figure 7: Design variation of the pencil-beam fed lens antenna in terms of the different values of n and θ_m

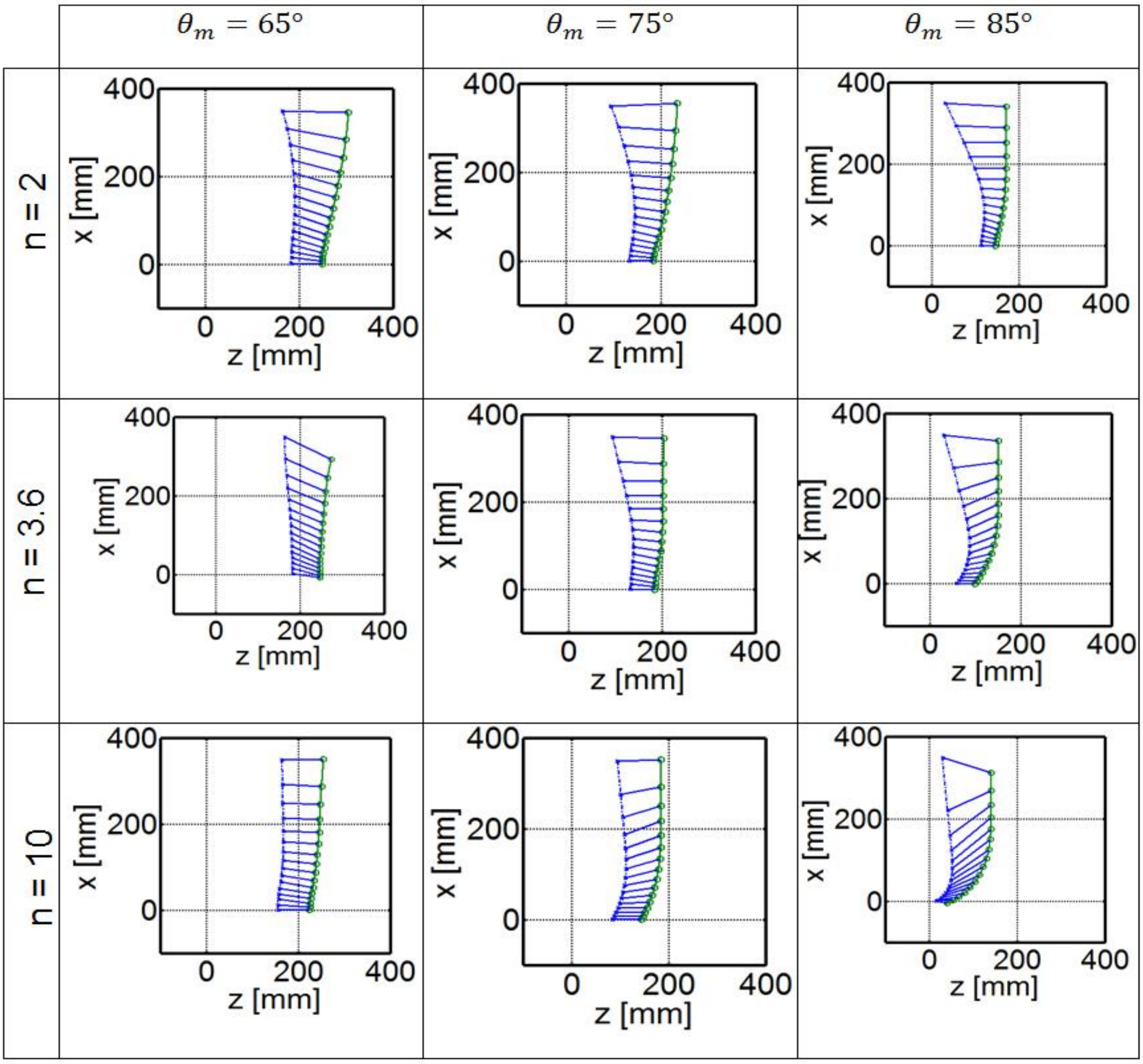

Figure 8: Design variation of the bifurcated-beam fed lens antenna in terms of the different values of *n* and θ_m